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Weed Management Systems for No-Tillage Vegetable Production

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1. Introduction

No-tillage (NT) is the extreme form of conservation tillage where the soil is left undisturbed before planting and crops are just planted into residues left on the soil surface (Morse 1999a). The direct seeding of large-seeded vegetables has generally provided successful crop establishment in NT production systems, although many vegetable crops can easily be transplanted in NT production systems including broccoli (*Brassica oleraceae* var. *italica*), cabbage (*Brassica oleraceae* var. *capitata*), cucumber (*Cucumis sativus* L.), pumpkin (*Cucurbita pepo* L.), squash (*Cucurbita pepo* L.) and tomato (*Solanum lycopersicum* L.) (Table 1). Planting is normally achieved in a narrow seedbed or slot created by a NT planter (Hebblethwaite 1997). No-tillage planters are typically equipped with coulters that cut through the mulch residue and disk openers that slice open the soil, with the seed or transplants then placed at proper depths in the soil profile. The opened soil is then closed with some type of device that presses the soil back together after the seed or transplants have been placed into the soil.

Vegetable Crop	Planting method	
	Direct seeded	Transplanted
Broccoli	Low	High
Cabbage	Low	High
Cucumber	High	High
Pumpkin	High	High
Summer squash	High	High
Tomato	Low	High

Low = poor likelihood of success using this method and High = great likelihood for success using this method.

Table 1. The likelihood of success for vegetable crop planting method in no-tillage production systems (adapted from Morse, 1999a)

1.1 Effects of No-Tillage systems

No-tillage systems are gaining increased attention by growers as a practical way to produce vegetables while improving soil quality parameters at the same time. Many vegetable growers are interested in NT production practices for many different reasons besides just

decreasing the overall cost of production. No-tillage provides several advantages to conventional tillage (CT; e.g., plowing and disking of soil) including reduced soil and wind erosion, soil water conservation and the addition of organic matter to the soil (Barnes & Putnam 1983, Blevins et al. 1971). However, an adverse effect of NT vegetable production is that organic mulches or residues on the soil surface significantly decrease soil temperatures, especially during the spring, which can significantly reduce seedling emergence and vigor, and delay vegetable crop maturity. This is especially important since the earliness of production is often important in the marketing and profitability of many vegetable crops. Walters & Young (2008) found that soil covered with winter rye (*Secale cereale* L.) residues used for NT zucchini squash production will generally provide about a 5 to 6°C reduction in soil temperature compared to bare soil. Walters et al. (2007) found that the use winter rye enhanced early cucumber yields under drought conditions, but early yields were suppressed when cooler weather conditions prevailed. Thus, early yields of many vegetables can be significantly affected when using cover crop residues depending on seasonal growing conditions.

1.2 Importance of weed control in No-Tillage systems

Although the loss of vegetable crop earliness can be a problem, the adoption of NT practices by commercial vegetable growers has been limited primarily due to the lack of effective weed management in this type of production system. Although all vegetation is often herbicide-killed before planting to achieve a weed-free, stale-seedbed in NT systems, vegetable growers have been reluctant to use NT production practices due to the problem of weed control. Several researchers (Hoyt & Monks 1996, Hoyt et al. 1996, Masiunas et al. 1995, Shelby et al. 1988, Walters & Kindhart 2002) indicate that NT significantly increases weed problems in vegetable production. Weeds often become the primary problem in NT production systems, since between-row tillage is often used to reduce weed populations that preemergence (PRE) herbicides fail to control in CT systems. Weedy fields have been a major deterrent to the adoption of NT vegetable crops, especially when growers failed to achieve uniformly distributed, high-residue mulched fields (Morse 1999b, Morse et al. 2001). Although NT provides greater overall weed control compared to conventional tillage, which most likely results from tillage promoting weed germination by exposing dormant seeds to oxygen and sunlight (Teasdale et al. 1991), effective weed control soon after crop emergence is essential during the early part of the growing season to prevent weeds from suppressing vegetable crop yield and quality. Current weed control programs in NT systems recommend the use of nonselective herbicides to kill the cover crop or control emerged weeds in residues, followed by an application of PRE and then postemergence (POST) herbicides. No-tillage systems often require more herbicides than do CT programs (Wallace & Bellinder 1992). Although herbicides are typically used as the primary means for weed control in NT vegetable systems, those available for most vegetable crops do not provide season-long weed control. Thus, effective weed management systems must be developed for NT vegetable production before NT will be widely utilized by growers.

1.3 Effects of No-Tillage on weed species and population densities

The use of NT production practices has a definite influence on the weed species composition and density. Tillage practices have a significant influence on weed population and species

composition by modifying the soil environment (Putnam et al. 1983). Weed species, soil seed density, seed production, and surface residue can all affect weed population dynamics under different tillage systems (Teasdale et al. 1991). Although cultivation generally stimulates weed emergence compared to NT production systems, the effects of NT on weed populations have been highly variable depending on environmental conditions as well as herbicide performance. Putnam (1986) and Putnam & DeFrank (1983) indicated that grasses and perennial weed species tend to dominate weed communities in reduced tillage systems over time, although shorter term studies have had mixed results (Masiunas et al. 1995, Teasdale et al. 1991). Research has indicated that although weed control by cover crop mulches lasts from about 30 to 75 days (Barnes & Putnam 1983, Creamer et al. 1996, Masiunas et al. 1995, Moore et al. 1994), weed species respond differently to cover crop mulches. Cover crop residues can also influence weed populations in NT cropping systems due to the proximity of the residue to the site of seed germination on the soil surface. Teasdale et al. (1991) indicated that tillage and cover crops can influence weed populations, the rate of population growth, and species composition. Seedling emergence of several weeds in NT was consistently suppressed by winter rye and wheat (*Triticum aestivum* L.) surface residues compared to CT (Blum et al. 1997). Generally, surface residues prevent germination of small seeded annual species that require light for germination, such as common lambsquarters (*Chenopodium album* L.) and various species of *Amaranthus* (e.g., redroot pigweed, *Amaranthus retroflexus* L.), whereas surface mulches do not generally prevent the germination of large-seeded annuals and perennials. Morse (1999a) indicated that fields planted to NT should not have serious perennial weed problems such as nutsedge (*Cyperus* spp.), quackgrass [*Agropyron repens* (L.) Beauv.], johnsongrass [*Sorghum halepense* (L.) Pres.], or morningglory (*Ipomoea* spp.). Furthermore, Masiunas et al. (1997) and Derken et al. (1993) indicated that prostrate pigweed (*Amaranthus blitoides* S. Wats.) was more common in CT than in cropping systems with surface residues. In NT and high residue mulch systems there tends to be more wind dispersed species [e.g., dandelion (*Taraxacum officinale* Weber)] than in CT (Bottenburg et al. 1997). Although NT cover crop systems reduce weed populations, the use of a residual herbicide is still required to prevent weed populations from increasing to severe field infestation levels. Kruidhof et al. (2009) indicated that the optimal cover crop residue management strategy for weed suppression depends on the cover crop species and the target weed species.

2. Production systems for No-Tillage vegetables

Several different production systems have been evaluated for NT vegetables. Although the vegetable crop planting method plays a major role in the successful production of NT vegetables (Table 1), the production system utilized for NT vegetables has shown to have a definite influence on the resulting productivity of the crop.

2.1 Bare soil systems

A bare soil NT system will improve weed control compared to CT (Moore et al. 1994, Walters et al. 2008), since the use of NT avoids bringing new weed seeds closer to the soil surface where they can germinate and increase weed densities (Derken et al. 1993). The presence of surface residue and lack of soil disturbance in NT were likely contributing factors that significantly influenced weed control even in the absence of herbicides (Walters et al. 2008). However, most growers will include cover crops when using NT for various reasons.

2.2 Cover crop based systems

Cover crops reduce the amount of soil erosion that is likely to occur compared to a bare soil system, as well as reducing water evaporation from the soil and increasing infiltration, generally resulting in greater soil moisture than bare soil systems. Cover crops will also provide additional weed control compared to that achieved with only a bare soil system. Furthermore, cover crops provide many other benefits that improve soil characteristics. A cover crop is any living ground cover that is planted into or after the primary crop and is commonly killed before the next crop is planted. The primary benefit of cover crops is reduction of water runoff and soil erosion, which ultimately results in improved soil productivity. Griffith et al. (1986) indicated that the use of cover crop residues for NT planting protects the soil surface from erosion by absorbing the impact of raindrops, thus reducing soil particle detachment and decreasing the acceleration of runoff; additionally, increased water infiltration and reduced soil water evaporation under NT generally increases plant-available water and subsequent crop yield potential. The presence of 1 to 2 Mg·ha⁻¹ of crop residues on the soil surface on sloping lands can reduce water runoff and soil erosion losses by 40 to 80% compared to bare soil (Meyer et al. 1970).

Cover crop residues are often used as part of a weed management program in vegetable cropping systems (Leather 1983, Masiunas 1998, Putnam 1986). Cover crop mulch systems modify the microenvironment, which has an impact on weed populations and vegetable crop yields (Masiunas 1998). Although the combination of NT and cover-cropping practices have certain advantages over traditional tillage (e.g., plowing and disking of soil), there has been limited research in vegetable crops, particularly when used in conjunction with chemical weed control (Rapp et al. 2004). Cover crops are often integrated into NT production systems for their weed suppressive ability and numerous researchers have attempted to use cover crops as a method for weed control in vegetable crop production.

2.2.1 Types of cover crops used in NT systems

Two types of cover cropping systems are typically used in vegetable production, winter and summer annuals. The majority of efforts have focused on fall seeded cereal grains (especially winter rye) or perennial legumes, such as clovers (*Trifolium* spp.) or vetches (*Vicia* spp.), although some research has been conducted on the use of summer annuals for use as living mulches. Winter annual cover crops have been successfully incorporated into NT production systems and are the most widely used type of cover crop in NT systems. Summer annuals are rarely used in vegetable production, although they can provide several advantages during the summer months including weed suppression, increasing nitrogen levels in soil for subsequent crops, preventing the leaching of soil nitrogen, improving soil physical properties, and adding organic matter to the soil.

Winter annual cover crops include many cereal grains such as barley (*Hordeum vulgare* L.), wheat, and winter rye, as well as legumes like clovers and hairy vetch (*Vicia villosa* Roth.). Cereals like winter rye or wheat are the most popular cover crops, since that are relatively easy to establish and fast growing, and the seed is readily available and relatively inexpensive. In contrast, legumes do not cover the soil as quickly, although they do improve soil nitrogen levels that can be used by the following crop. An ideal cover crop should prevent erosion, suppress weeds, scavenge excess nutrients, and add organic matter back into the soil. Small grain cover crop residues suppress weeds by modifying light, temperature, moisture, and the chemical environment of germinating weeds (Putnam 1986,

Teasdale et al. 1991). Small-seeded annual weed species, such as redroot pigweed and common waterhemp (*Amaranthus rudis* Sauer), require light for germination and residues on the soil surface will prevent germination (Teasdale et al. 2004); however, as straw mulch residues decompose, more light reaches the soil surface, resulting in germination of these small seeded annual weeds and greater weed pressures later in the growing season. Thus, small grain cover crops can contribute to weed control in NT systems but herbicides or other weed control tactics are generally necessary to obtain optimal weed control and crop yield.

Several different cereal grains are often used as cover crops for vegetable production (Masiunas 1998). Barley is a fast growing, cool season, annual grain crop that can be used as a cover crop for vegetable plantings. This plant can provide nonchemical weed suppression, as it will often shade and smother weeds, or provide competition for soil moisture and nutrients. In addition, barley has an allelopathic effect on weed germination. Although winter wheat is typically grown as a cash grain crop, it can provide similar benefits as other cereal crops. It has shown to work well in NT systems for weed control and will generally provide similar results as winter rye (Walters & Young 2010). Winter rye is one of the best winter hardy cover crops as it overwinters well and produces considerable biomass (Putnam 1986, Weston 1990). It is also effective at capturing nutrients from soils and provides a persistent weed suppressive mulch during the summer, although it can remove soil moisture and immobilize nitrogen. However, some type of additional weed control is generally required with winter rye residue to provide season-long suppression of weeds (Masiunas et al. 1995, Teasdale 1993).

Many types of legumes can also be used in NT vegetable production systems. Although there are many types of clovers that can be included as cover crops, white clover (*Trifolium repens* L.) has been widely used in various vegetable crops. They are widely adapted perennial nitrogen producers that protect soils from erosion and suppress weeds. White clovers can be used in living mulch systems, as they can be broadcast over vegetables in late spring to establish under the primary vegetable crop (Infante and Morse 1996). This plant tends to grow slowly while shaded, and then grows more rapidly when it receives more light. Hairy vetch is widely used as a winter annual legume cover crop. It will consistently produce high biomass to suppress weeds with high nitrogen content and can be easily killed in the spring by herbicides, mowing, or rolling (Teasdale 1999). Teasdale (1993) also observed that light reduction may be more important than allelopathy or physical impedance for weed suppression by hairy vetch residues. However, it only captures limited amounts of nutrients from soils during the fall and winter and will only suppress weeds for a limited amount of time due to rapid decomposition.

Cover crop research has focused primarily on winter annual crops, although summer annual cover crops have potential applications in many regions. There are several summer annual cover crops that can be used including buckwheat (*Fagopyrum esculentum* Moench), sorghum-sudangrass [*Sorghum X drummondii* (Steudel) Millsp. & Chase], and soybean [*Glycine max* (L.) Merr.] (Creamer & Baldwin 1999). These plants when grown at close spacings will completely shade the soil surface which will suppress and outcompete weed growth. Buckwheat can be grown during the summer months and will effectively suppress weed growth and recycle nutrients. Sorghum-sudangrass is a warm-season annual grass that grows well under hot, dry conditions and will produce high amounts of biomass; it is also very effective at suppressing weeds, reducing soil erosion, and recycling nutrients. Soybean produces an erect, bushy plant that establishes quickly, improves nitrogen fertility in the soil, and suppresses weeds.

2.2.2 Effects of intercropping cover crops for NT systems

Intercropping of different cover crop species can overcome some of the problems associated with the use of a single cover crop species. The intercrop mixture of winter rye and hairy vetch is widely used for vegetable production as it produces more biomass, does a better job at protecting the soil, and provides better weed suppression than either species grown alone (Mangan et al. 1995, Schonbeck et al. 1993). Winter rye intercropped with hairy vetch provided 50% fewer weed seedlings compared to hairy vetch alone (Burgos & Talbert, 1996). Many research studies have indicated that cover cropping systems using winter rye in combination with hairy vetch can significantly suppress weeds in NT vegetable production systems and in some instances, can eliminate the need for additional weed control. However, in most situations, additional weed control measures will need to be implemented as the use of cover crops alone will generally provide insufficient total-season weed control.

2.2.3 Management of cover crops in NT systems

There are two basic approaches that are generally used in managing cover crops (Paine & Harrison 1993). In mulch residue systems, the cover crop growth is killed in some manner before planting the vegetable crop, whereas in living mulch (LM) systems, the companion crop grows at the same time as the vegetable crop. The cover crop management system used in NT really depends on the particular vegetable crop that is being grown, as certain crops are more amenable to residue mulch systems while others can be managed in living mulch systems.

Cover crops to be left on the soil surface for NT production must be killed, either with herbicides or in a mechanical manner (Creamer & Baldwin 1999). Fall planted cover crops, such as wheat or winter rye, are often herbicide-killed in the spring. Nonselective contact herbicides, such as glyphosate or paraquat dichloride, are often used to desiccate cover crops as well as other perennial and immature annual weeds growing in the field; and, these herbicides should be used within two weeks of seeding or transplanting the vegetable crop to ensure complete vegetative kill, otherwise another application will have to be made to kill the weeds that are present. Although many cover crops are herbicide killed, there are several methods for mechanically killing cover crops including undercutting, mowing and rolling. A rolling stalk chopper or similar device can also be used to roll down cover crops. Flail mowing and rolling can effectively kill mature winter rye, hairy vetch, crimson clover, wheat, and mixtures of winter rye and hairy vetch (Dabney et al. 1991).

Living mulches are cover crops planted either before or with the primary crop and are maintained as a living ground cover throughout the growing season of the crop. Living mulches grow alongside or within a vegetable crop and can significantly reduce weed populations, but they can often be difficult to manage in vegetable cropping systems because they compete with the crop. The use of LMs can minimize erosion, decrease soil temperatures, improve the rate of water infiltration, improve soil structure, enhance soil microbial activity and increase crop yield (Hartwig & Ammon 2002). Since LMs can compete for moisture and nutrients, they are not recommended for low-growing, shallow-rooted, or drought-susceptible vegetable crops. Various grasses, legumes, and *Brassica* species have been used as living mulches for NT vegetable production. Those LMs that are seeded and established shortly before the vegetable crop is planted tend to provide less competition to the crop and less weed suppression than those established several months prior to planting

of the vegetable crop (Masuinas 1998). The success of a LM in reducing weed populations depend on its ability to rapidly establish a ground cover and smother weeds without competing with the vegetable crop (Putnam 1990). Living mulches that have been used in vegetable production include perennial ryegrass (*Lolium perenne* L.), creeping red fescue (*Festuca rubra* L. subsp. *commutate*), ladino clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.), and sorghum [*Sorghum bicolor* (L.) Moench]. Perennial ryegrass is low growing and will usually not grow higher than the vegetable crop which allows the vegetable crop to photosynthesize at somewhat a normal rate. Although clovers improve nitrogen fertility of soils, most clovers are low growing and produce allelochemicals (Harborne 1987) that suppress weed populations. However, LMs, such as perennial ryegrass, sorghum, and clovers compete with vegetable crops for light, moisture and nutrients (Shennan 1992). Bottenberg et al. (1997) and Masuinas et al. (1997) indicated that perennial ryegrass provided a better LM than did red clover in cabbage production; perennial ryegrass did not grow above the cabbage foliage, but the growth of red clover was able to overtop the cabbage which restricted light from reaching the crop canopy causing yield reductions.

The application of low herbicide rates may reduce the competitiveness of LMs, allowing their use in vegetable production. However, Walters & Young (2008) found that a NT herbicide suppressed winter rye LM system provided excessive amounts of zucchini squash stunting which significantly reduced yield. Nicholson & Wien (1983) also suggested that light competition between a white clover LM and cabbage probably reduced crop yields due to the shading of lower cabbage leaves by excessive clover growth. In contrast, Infante & Morse (1996) indicated that legumes intentionally seeded (or interseeded) into a standing crop can be effectively established in NT after transplanting broccoli to suppress weeds without reducing crop yield. Although interseeded cover crops often suppress weeds, they also generally result in vegetable crop yield reductions compared to other more conventional weed management practices. These reductions in crop yields are often due to the direct competition between the cover crop and the main crop. Although Masiunas et al. (1997) found that a hairy vetch LM established before transplanting cabbage would suppress weeds, it would eventually grow above the cabbage canopy later in the growing season and reduce yields. The delayed seeding of cover crops has been an effective means of minimizing yield losses in many crops including broccoli (Brainard & Bellinder 2004). Furthermore, Brainard et al. (2004) found that hairy vetch seeded at 20 days after transplanting cabbage might provide an alternative for weed control in this crop since it: 1) provides significant biomass for soil improvement; 2) does not reduce cabbage yields; and 3) provides some weed suppression.

Living mulches are more difficult to manage than conventional cropping systems and are not suitable in all situations. The interspecific competition for light, water, and nutrients between the LM and vegetable crop can limit the use of the system (Fisher & Burrill 1993; Galloway & Weston 1996). The careful selection of less vigorous genotypes is essential for the success of living mulches for vegetable production systems (Nicholson & Wien 1983). Furthermore, the competitiveness of LMs can be reduced by using strip tillage systems, mowing, or using reduced rates of herbicides (Hoyt et al. 1994, Paine & Harrison 1993).

2.2.4 Effects of allelochemicals produced by cover crops for NT systems

Cover crop mulches often release allelochemicals that aid in suppressing weed populations. Those cover crops that contain a high level of allelochemicals are well-suited for mulch

residue mediated weed suppression. The soil surface coverage provided by cover crops mulches often correlate with weed suppression (Teasdale et al. 1991). The amount of soil surface coverage is important since mulches block the light stimulus that is required for the germination of many small seeded weed species (Barnes & Putnam 1983, Moore et al. 1994, Teasdale 1993). When cover crops, such as winter rye, are incorporated into the soil, the resulting weed control is often significantly reduced (Walters & Young 2010, Walters et al. 2008), which is most likely due to several factors including less soil surface coverage by mulch residues, bringing new weed seed to the soil surface, quicker decomposition of incorporated residues, and lower levels of allelochemicals in the weed seed germination zone (Masiunas 1998). Generally, once cover crop residues are incorporated into the soil, allelochemicals quickly decompose and are leached away from the upper soil levels where weed seeds germinate (Dias 1991). In contrast, when cover crop residues remain on the soil surface, weed growth is suppressed for a longer period of time since allelochemicals degrade slower (Masiunas 1998).

The residues of many cover crops release allelochemicals that inhibit weed seed germination and growth (Creamer et al. 1996, Mwaja et al. 1995, Ohno et al. 2000, Weston 1996). Wheat residues contain ferulic acid (4-hydroxy-3-methoxycinnamic acid) which has been shown to inhibit the germination and root growth of many important weeds including large crabgrass (*Digitaria sanguinalis* (L.) Scop.), pitted morningglory (*Ipomoea lacunosa* L.), common ragweed (*Ambrosia artemisiifolia* L.), and prickly sida (*Sida spinosa* L.) (Hicks et al. 1989, Liebl & Worsham 1983). Furthermore, in barley, the alkaloid gramine has been shown to inhibit weed growth (Harborne 1987). Sorghum residues have been shown to contain the phenolic compounds, p-coumaric, m-hydroxybenzoic, and protocatechuic acids which can inhibit weed seed germination and seedling growth (Lehle & Putnam 1982, Panasiuk et al. 1986, Weston et al. 1989). Oil seed rape (*Brassica napus* L.) releases glucosinolate breakdown products, including isothiocyanates, oxazolidinethiones, ionic thiocyanate and organic cyanides (Brown & Morra, 1996, Haramoto & Gallandt 2004).

Compared to other cover crops, the effect of allelochemicals on weed suppression has been extensively studied in winter rye. This cover crop is especially important since it has been widely documented to suppress the density of weeds in NT production systems (Barnes & Putnam 1983, Teasdale et al. 1991, Weston 1990, Zasada et al. 1997). Putnam & DeFrank (1983) reported that winter rye reduced the emergence of common ragweed by 43%, green foxtail [*Setaria viridis* (L.) Beauv.] by 80%, redroot pigweed by 95% and common purslane (*Portulaca olearacea* L.) by 100%. Shilling et al. (1985) indicated that winter rye residues used in a NT system reduced the biomass of common lambsquarters by 99%, redroot pigweed by 96% and common ragweed by 92% compared to a non-mulched tilled control. Barnes & Putnam (1983) found that winter rye provides better weed control if allelochemicals are actively produced in roots and released into the soil; and, once the winter rye plant dies, most weed control is achieved through the decaying mulch on the soil surface simply providing a physical barrier to weed germination and growth. Furthermore, Yenish et al. (1995) reported that the duration of weed suppression by a winter rye cover crop more closely follows the disappearance of allelochemicals from residues than the disappearance of the residue itself. The decomposing winter rye residues on the soil surface produce a wide range of allelochemicals including phenylacetic acid, 4-phenylbutric acid, 2,4-dihydroxy-1,4-benzoxazin-3-one (DIBOA), and 2-benzoxazoline (BOA). Both DIBOA and BOA have been shown to inhibit germination and seedling growth of several grass and broadleaf weed species (Barnes & Putnam 1983, Chase et

al. 1991, Creamer et al. 1996, Shilling et al. 1985). The amounts of DIBOA and BOA found in rye often correlates with the inhibition of weed growth (Mwaja et al. 1995, Yenish et al. 1995). Furthermore, Chase et al. (1991) indicated that large-seeded weed species or those species that have deeper seed placement in the soil profile were less affected by allelochemicals produced by winter rye, which was most likely due to higher concentrations of allelochemicals near the soil surface where small-seeded species typically germinate. The decline in DIBOA concentrations as winter rye matures, and the fact that many winter rye cultivars mature at different rates, may partially explain the discrepancies observed in previous studies from weed suppression from winter rye (Reberg-Horton et al. 2005).

Although the allelopathic potential of hairy vetch and other legume cover crops have been documented, weed suppression by legumes is generally less compared to grass cover crops. Hairy vetch residues contain many different compounds including alcohols, aldehydes, furans, and monoterpenes which have the ability to suppress weed growth (Bradow & Connick 1990). Hairy vetch residues decompose more rapidly than those of winter rye (Mohler & Teasdale 1993, Schonbeck et al. 1993) and surface coverage by hairy vetch residues has been shown to be more important for weed control than allelochemical release (Curran et al. 1994, Teasdale et al. 1991). Therefore, weed control by hairy vetch residues is lower compared to that obtained by winter rye residues.

3. Importance of herbicides for No-Tillage vegetables

Some type of herbicide application is generally required to optimize weed control and maximize vegetable productivity in NT systems, since cover crop residues can generally be expected to provide early-season weed suppression (for about the first 4 to 6 weeks) but not full-season weed control. In NT squash (Walters et al. 2004, 2005) and cucumber (Walters et al. 2007) production systems, the use of winter rye enhanced weed control even when a standard herbicide program was used. In NT pumpkin production, redroot pigweed and common waterhemp control was achieved early in the growing season with only winter rye residues but control was not sustained throughout the growing season and required some other method of weed management, such as herbicides, to optimize control (Walters et al. 2008). As stated earlier, broadleaf weed control is a major problem in NT vegetable production systems because there are few herbicides available in most vegetable crops to control these weeds, and the number of available herbicides is dependent on the specific vegetable grown. Although there are several PRE herbicides available for many different vegetable crops, the emergence of weeds after soil residual herbicides have lost their activity often leads to excessive weed populations later in the production season. In comparison, between-row tillage is often used in CT to reduce weed populations that PRE herbicides fail to control.

3.1 Preemergence herbicides for No-Tillage vegetables

Preemergence herbicides are widely used in NT vegetable production to control weeds. These are applied to the soil surface prior to crop or weed emergence, and when transplants are used, they are generally applied to weed-free soil before transplanting. Preemergence herbicides should be effective for at least 30 days, since this would prevent establishment of early germinating weeds from providing excessive competition to vegetable plants. Stall (2001) indicated that weeds emerging during the first four weeks of cucurbit crop

establishment will suppress crop yield, while those emerging after this time period will generally not reduce yields.

There are only a few labeled PRE herbicides for use in NT production systems for cole crop, cucurbit and solanaceous vegetables, including bensulide, clomazone, ethalfluralin, halosulfuron-methyl, napropamide, oxyfluorfen, rimsulfuron, and S-metolachlor (Table 2). Bensulide is applied either preplant or PRE in many vegetable crops, especially many of those within the cole crop, cucurbit, and solanaceous vegetable groups. However, the delay of irrigation or rainfall to activate this herbicide in the soil by more than 36 hours may result in poor weed control. Although this herbicide is registered for control of many different annual grasses and a few broadleaf weeds, it tends to provide only marginal weed control even at low weed infestation levels. Clomazone has been registered for a number of vegetable crops for many years, and is a valuable herbicide that is critical for weed control programs in several crops, including cabbage and some cucurbits. Although clomazone is an excellent PRE grass herbicide, it only controls a limited number of broadleaf weed species. Ethalfluralin is a PRE herbicide that provides control of a few broadleaf and grass weeds in cucurbit vegetable crops. However, clomazone and ethalfluralin are typically sold as a pre-mix that is used in cucurbit vegetable crops. Prior to the labeling of halosulfuron-methyl and S-metolachlor for pumpkin, this clomazone and ethalfluralin pre-mix was widely used by most growers since it provided control of many different weed species. The bleaching of crop and weed leaves will often be observed due to the clomazone component in the mixture. The clomazone and ethalfluralin pre-mix will provide PRE control of annual grasses and many broadleaf weeds including common lambsquarters, various pigweed

Herbicide	Vegetable crop	Application	Weeds controlled
Bensulide	Br, Ca, Cu, Pu, Sq	PRE	Broadleaves, grasses
Clethodim	Br, Ca, Cu, Pu, Sq, To	POST	Grasses
Clomazone	Ca, Cu, Sq	PRE	Broadleaves, grasses
Clomazone + Ethalfluralin	Pu, Sq	PRE	Broadleaves, grasses
Ethalfluralin	Pu, Sq	PRE	Broadleaves, grasses
Halosulfuron-methyl	Pu, Cu, To	PRE, POST	Broadleaves, nutsedges
Metribuzin	To	PRE, POST	Broadleaves, grasses, nutsedges
Napropamide	Br, Ca, To	PRE	Broadleaves, grasses
Oxyfluorfen	Br, Ca	PRE	Broadleaves
Rimsulfuron	To	PRE	Broadleaves, grasses
S-metolachlor	Pu, To	PRE	Broadleaves, grasses, nutsedges
Sethoxydim	Br, Ca, Cu, Pu, Sq, To	POST	Grasses

Br = Broccoli, Ca = Cabbage, Cu = Cucumber, Pu = Pumpkin, Sq = Squash, To = Tomato. PRE is preemergence to weed emergence and POST is postemergence to vegetable crop. The herbicides, bensulide, clomazone, ethalfluralin, metribuzin, napropamide, oxyfluorfen, rimsulfuron, and S-metolachlor provide control of only a limited number of broadleaf or grass weed species. The control of specific weed species by halosulfuron-methyl or metribuzin depends on whether applied PRE or POST. Nutsedges are *Cyperus* spp.

Table 2. Selected herbicides for use in no-tillage production systems for various vegetable crops.

species, common purslane, velvetleaf (*Abutilon theophrasti* Medik), common ragweed, and Pennsylvania smartweed (*Polygonum pensylvanicum* L.). Halosulfuron-methyl is a herbicide that can be used both PRE and POST in cucurbit vegetable crops and several different fruiting vegetables including tomato. Although this herbicide will provide PRE control of many different broadleaf weeds, it provides no grass weed control and only suppresses yellow (*Cyperus esculentus* L.) and purple nutsedge (*Cyperus rotundus* L.). Heavy rains following PRE applications of halosulfuron-methyl can often lead to severe crop injury. Napropamide can be applied PRE to either direct seeded or transplanted cole crops, such as broccoli and cabbage, and solanaceous fruiting vegetables including pepper (*Capsicum annuum* L.) and tomato. Although napropamide does not control established weeds, it will provide PRE control of numerous annual broadleaf and grass weeds. Oxyfluorfen can be used PRE in both broccoli and cabbage crops as a pre-transplant treatment to provide control of carpetweed (*Mollugo verticillata* L.), redroot pigweed, common purslane, and Pennsylvania smartweed. Pre-transplant applications of oxyfluorfen may result in early leaf cupping or crinkling crop injury and is more severe if crop leaves directly contact treated soil, although crops will rapidly outgrow this injury. However, more severe crop injury will result if transplants are under some type of stress. It is important to note that oxyfluorfen should not be applied to soil if an acetanilide herbicide such as S-metolachlor has been applied to the field during the current growing season as severe crop injury may occur. Rimsulfuron can be used PRE in tomato for the control of a wide variety of broadleaf and grass weeds, although it will only provide partial control of weeds such as crabgrass (*Digitaria* spp.), common cocklebur (*Xanthium strumarium* L.), common lambsquarters, common ragweed, velvetleaf, and black (*Solanum nigrum* L.) and hairy nightshade [*Solanum villosum* (L.) Mill.]. Preemergence applications may not provide adequate control of weeds > 2.5 cm in height or weeds that have an established root system prior to the activation of rimsulfuron. S-metolachlor can be applied PRE in NT pumpkins and tomatoes for control of numerous grasses and broadleaf weeds, as well as yellow nutsedge. S-metolachlor will not control emerged weeds and must be applied to a weed-free soil or in tank mixtures with products that provide POST control of weeds present at the time of application; tank-mixtures of S-metolachlor with a contact herbicide (glyphosate or paraquat dichloride) can be used to provide POST control of many weeds, with later germinating weeds controlled by S-metolachlor.

It is important to note that moisture is essential for activation of these PRE herbicides once they have been applied. Within 5 to 7 days after application, about 12 to 25 mm of rainfall or sprinkler irrigation is needed to activate most PRE herbicides used in vegetable production. If adequate moisture is not provided during this time period then weed control provided by PRE herbicides will be drastically reduced. For those herbicides that can be used PRE and POST, if moisture cannot be managed via rainfall or sprinkler irrigation, allowing weeds to emerge and then applying POST will most likely result in better weed control.

3.2 Postemergence herbicides for No-Tillage vegetables

The use of effective POST herbicides for control of annual grass and broadleaf weeds is important to achieve success in NT vegetable production systems. Hoyt et al. (1994) indicated that the lack of effective POST herbicides is a problem for NT vegetable production systems. Although grass weeds can be effectively controlled in most vegetable crops with minimal effort, many difficult to control broadleaf weeds are not sufficiently

controlled due to the lack of effective herbicides that can be sprayed POST. Postemergence grass control can usually be obtained in most vegetables with the use of clethodim or sethoxydim. Both of these herbicides are widely used selective POST herbicides that control annual and perennial grass weeds in broadleaf vegetable crops. Although several vegetable crops including cabbage, cucumber, pumpkin, and tomato have registered POST broadleaf weed herbicides which have been successfully used in NT systems, many vegetables crops including squash lack labeled effective POST broadleaf herbicides. There are a limited number of POST herbicides labeled for broadleaf weed control in NT cole crop, cucurbit and solanaceous vegetables, including halosulfuron-methyl, metribuzin, and rimsulfuron. Although halosulfuron-methyl is often applied PRE, POST applications can be made to established plants of cucumber, pumpkin and tomato for control of yellow nutsedge, redroot pigweed, velvetleaf, common ragweed, and many other broadleaf weeds. For optimum control of yellow and purple nutsedge, sequential applications on areas where this weed has emerged or re-grown may be required. However, there is the potential for crop stunting and a slight maturity delay with the use of halosulfuron-methyl when used POST. Many times, POST applications will often extensively slow the growth of cucurbit vines. To reduce injury, it can also be used as a directed POST application to row middles for many different vegetable crops. If halosulfuron-methyl is applied POST on drought stressed weeds, its activity will most likely be reduced and the resulting control is often inadequate. The carryover from halosulfuron-methyl is 0 to 36 months depending on the next crop that is grown and this should be considered when this herbicide is used. Metribuzin is often applied POST in established tomatoes and provides effective control of many different broadleaf weeds and a few grass weeds. Repeated POST applications of metribuzin are often required to provide optimal control of several weeds such as jimsonweed (*Datura stramonium* L.), common ragweed, and velvetleaf. If applications are made to tomato growing under stressful conditions, crop injury or delayed maturity may result. Rimsulfuron can be used POST in tomato to control a wide range of broadleaf and grass weeds. Weed control is best achieved when POST applications of rimsulfuron are made to actively growing weeds that are less than 2.5 cm in height. Applications should be made after tomato plants reach at least the cotyledon stage. Similar to metribuzin, if applications are made to tomato growing under stressful conditions, temporary crop chlorosis may occur, but symptoms normally disappear within 2 weeks. To optimize weed control in tomato, PRE and then POST or sequential POST applications of rimsulfuron can be made.

4. No-Tillage vegetable cropping systems

4.1 Brassicas

4.1.1 Cabbage

Several researchers found that cabbage yields in NT were similar to that of CT (Hoyt et al. 1996, Morse 1995, Morse & Seward 1986), although Knavel and Herron (1981) indicated that spring cabbage yields were reduced in NT when compared to CT. Wilhot et al. (1990) related cabbage yield reductions in NT to poor plant establishment/impaired crop growth more than to the effects of a NT production system. Furthermore, similar to what has been observed for other vegetable crops, when weed control methods and PRE herbicides were used in NT cabbage, yields were similar to those of CT (Bellinder et al. 1984).

Weed control has been the limiting factor for implementation of NT cabbage production systems. Masiunas et al. (1997) indicated that the cropping system utilized affected both broadleaf and grass weed densities in NT cabbage production. Although winter rye mulch is often utilized in NT cabbage production, Morse & Seward (1986) indicated that hairy vetch and Austrian winter pea [*Pisum sativum* spp. *arvense* (L.) Poir.] were better mulch covers than winter rye for NT cabbage production, which was most likely due to the nitrogen released by the two legumes through mineralization of the plant residues. Furthermore, Schonbeck et al. (1993) indicated that hairy vetch produced greater cabbage yields than winter rye, which was most likely due to the immobilization of soil nitrogen due to the high carbon to nitrogen ratio in winter rye. In contrast, Masiunas et al. (1997) found that the use of fall-seeded winter rye was the most promising mulch system in NT cabbage for weed suppression; and, the weed suppression obtained from the winter rye NT system was similar to that obtained from CT using trifluralin applied PRE. Winter rye mulch suppressed broadleaf weed emergence for 6 weeks compared to CT (Masiunas et al. 1997). Living mulches also show some potential for suppressing weeds in cabbage and other *Brassicas*. The use of LMs for all or part of a *Brassica* crop growing season is becoming of interest to growers to extend weed control for a more sustainable weed management system. The integration of cover crops by interseeding into an established vegetable crop may serve to provide a more effective way to manage weeds. Castello (1994) found that broccoli head size and weights in a NT living mulch system using white clover was similar to that produced in CT. In contrast, Brandsaeter et al. (1998) found that clover interseeded in cabbage provided some late-season weed suppression, but this alternative weed management strategy tended to reduce cabbage yields.

4.1.2 Broccoli

Broccoli is a crop that can be easily produced in a NT production system. Abdul-Baki et al. (1997) found that fall-produced broccoli yields were similar between NT and CT production systems when surface residues from a killed summer cover crop provided sufficient soil coverage in the NT system. Furthermore, Morse (1995) indicated that yields of broccoli grown in NT increased by about 10% compared to CT. Broccoli transplant establishment in NT was found to be similar or better compared to CT, which directly related to the high yields observed in NT (Infante and Morse, 1996). Lastly, Morse (2000) indicated that broccoli yields increased in a NT cover crop mulch system compared to a NT bare soil system.

Production systems for NT broccoli can often be successful without using herbicides, when appropriate high-residue cover crops are effectively killed by flail mowing or rolling and broccoli transplants are properly established and maintained in these evenly distributed cover crop mulches (Morse 1999b). Morse (2001) indicated that the use of a winter rye and hairy vetch mixture that was rolled in the spring was the best combination evaluated for production of NT summer broccoli. The use of forage soybean or foxtail millet (*Setaria italica* L.P. Beauv) mulch alone or in combination provided NT yields that were similar to CT, with applied herbicides having little influence on broccoli productivity (Abdul-Baki et al. 1997). Although NT broccoli yield is inversely correlated with the amount of weed biomass produced (Morse 2001), the use of herbicides can be reduced when large, vigorous transplants of broccoli are set in narrow double-rows in persistent, heavily mulched NT production systems, since this will result in significant amounts of weed suppression.

Many different cover crops and herbicides have been utilized to improve NT broccoli production. Broccoli produced larger heads and higher yields in a NT system utilizing a

combination of a legume (e.g., hairy vetch) with winter rye than with winter rye alone or no cover crop (Mangan et al. 1995). Although cover crops, such as winter rye or hairy vetch, integrated into NT *Brassica* crop production systems improve weed control, the use of herbicides is still required to provide a more effective weed management system. Hoyt et al. (1996) indicated that the use of oxyfluorfen PRE prior to transplanting significantly improves weed control and increases the success of using NT for cabbage production. The application of pretransplant herbicides, such as metolachlor or oxyfluorfen, generally reduces weed biomass in NT broccoli production (Abdul-Baki et al. 1997). Although there are many PRE or pre-transplant herbicides available for use in NT broccoli and cabbage, the lack of POST herbicides for broadleaf weed control still remains a major hindrance to the adoption of NT practices, since the lack of late-season broadleaf weed control will affect both yield and harvest efficiency.

4.2 Cucurbits

4.2.1 Cucumber

Similar to many other vegetable crops, cucumbers are generally managed with CT practices, such as plowing and repeated cultivations (Lonsbary et al. 2004). Weston (1990) found that cucumber, similar to most other cucurbits, was easy to establish in NT culture. Ogutu & Caldwell (1999) found that the use of cucumber transplants provided more biomass accumulation at 3 weeks after planting in NT resulting in higher early yields due to earlier flowering and fruit set than those that were direct seeded. Furthermore, although pickling cucumber leaf number, leaf area index and vine growth were reduced by NT, no reduction in total yield was observed compared to CT; and, the reduced vegetative growth in NT may actually be an advantage for the mechanical harvesting of this crop (Lonsbary et al. 2004). Adequate weed control in NT cucumber production systems must be achieved in some manner before this system will be widely used for this crop (Walters et al. 2007). The most consistent establishment of cucumber plants in NT occurred in winter wheat or rye residues, which provided a substantial level of weed suppression for at least 60 days following herbicide application to cover crops (Weston 1990). Walters et al. (2007) indicated that a winter rye cover crop alone would provide some but not sufficient, season-long redroot pigweed and smooth crabgrass [*Digitaria ischaemum* (Schreb. ex Schweig.) Schreb. ex Muhl.] control for cucumber grown in NT. Although broadleaf weed control is improved, herbicide-killed winter rye will not sufficiently suppress many difficult-to-control broadleaf weeds (depending on seasonal growing conditions) in NT cucumber production even if used with the standard PRE herbicide combination of clomazone + ethalfluralin + halosulfuron.

Weaver (1984) indicated that if cucumber plants are kept weed-free for the first four weeks after planting, yields would be similar to those kept weed free for the entire growing season. Thus, an appropriate PRE herbicide would appear to need a residual period of 24 to 36 days, as this would prevent establishment of early germinating weeds which provide excessive competition to young cucumber seedlings (Friesen 1978). Although cucumber will provide some weed suppressive ability once it forms a vine across the soil surface, other weed control measures are generally necessary to achieve adequate weed control.

The use of clomazone and ethalfluralin does not provide consistent satisfactory weed control in NT cucumber culture (Ogutu & Caldwell 1999, Walters et al. 2007). The PRE herbicide mixture of clomazone + ethalfluralin + halosulfuron provides both broadleaf and

grass weed control and high cucumber yields in a NT production system when used in combination with a winter rye cover crop (Walters et al. 2007). However, many-difficult to control broadleaf weeds are not adequately controlled by these herbicides when used PRE in a cover crop residue NT system, which often provides various problems for cucumber growers including yield suppression and reduced harvest efficiency. An advantage for cucumber compared to squash is that halosulfuron can also be used POST to suppress many difficult-to-control broadleaf weeds.

4.2.2 Squash

Many squash growers are interested in NT production because of the ecological and potential economic benefits provided by this type of production system. Growers tend to apply PRE herbicides regardless of whether CT or NT is used, with squash seeded before herbicide treatment or transplanted in herbicide treated soil. However, the emergence of weeds after soil residual herbicides have dissipated leads to excessive weed problems during fruit harvest (Walters et al. 2005). Harvesters cannot locate squash fruit as easily on plants that are shaded by weeds compared to those growing in a weed-free field, and this contributes to reduced harvest efficiency and yield loss. Several studies have indicated that squash grown in NT have similar yields to those grown in CT (Knavel & Herron 1986, NeSmith et al. 1994, Walters & Kindhart 2002, Walters et al. 2005), although yields were only comparable if weeds were adequately controlled. Since a major limitation to NT squash production is weed control, improved weed management practices must be developed before NT systems in this crop will be readily adopted.

Although clomazone + ethalfluralin is the PRE herbicide mixture most often utilized by squash growers, it often provides poor control of certain broadleaf weeds, such as the various species of *Amaranthus*. Walters et al. (2004, 2005) found that a PRE application of clomazone + ethalfluralin resulted in the best overall weed control without having a detrimental effect on zucchini squash yields in NT. Although applying clomazone + ethalfluralin PRE to winter rye residues in NT squash production improved redroot pigweed control compared with no herbicide, the level of control was generally not adequate (< 85% control) by 8 weeks after planting (Walters et al. 2005). Clomazone + ethalfluralin did not provide sufficient season-long weed control, which especially caused problems in locating squash fruit during hand-harvesting. Walters et al. (2004) indicated that although the herbicide clomazone and the no-herbicide produced high early-season squash yields in NT culture, the productivity in these treatments declined as weed pressures increased due to limited weed control. The PRE herbicide combinations of clomazone + ethalfluralin and clomazone + imazamox provided the best overall weed control without having detrimental effects on squash yields in a NT system (Walters et al. 2005).

Living mulch systems have been shown to generally result in crop yield reductions compared to more traditional weed control methods (Liebman & Staver 2001, Teasdale 1998, Wiles et al. 1989). Walters & Young (2008) found that a NT winter rye living mulch system provided excessive amounts of zucchini squash stunting which significantly reduced yields. Furthermore, as a living mulch in NT squash production, winter rye resulted in 80 and 82% control of redroot pigweed and smooth crabgrass about 8 weeks after transplanting, respectively, in the absence of herbicides compared to the no herbicide bare soil system (Walters & Young 2008).

Few herbicides are labeled for squash production and none will consistently provide season-long weed control (Walters et al. 2004), since most, except the POST grass herbicides, are

only labeled for PRE applications. Herbicides available for use in squash include bensulide (PRE), clethodim (POST), clomazone (PRE), ethalfluralin (PRE), and sethoxydim (POST) (Table 2). Although the PRE combination of clomazone + ethalfluralin is widely used in squash production, the weed control provided by this herbicide combination is generally inadequate. Due to the limited number of herbicides and inadequate weed control of those herbicides available for use in summer squash, registration of additional herbicides or the development of alternative methods of weed control is needed to allow for the widespread use of NT in this crop (Walters et al. 2004).

4.2.3 Pumpkin

Several studies have all indicated that NT and CT produce comparable pumpkin yields when sufficient weed control is achieved in NT production systems (Galloway & Weston 1996, Rapp et al. 2004, Walters et al. 2008). Pumpkin vegetation will provide some soil shading and weed suppression once vines form across the soil surface, but other weed control measures are generally necessary to achieve adequate weed control in NT pumpkin production. The use of herbicides and cover crops often play an important role in the management of weeds in NT pumpkin production.

The use of effective herbicides in combination with cover crops integrated into NT planting systems may provide a feasible option for pumpkin growers trying to enhance weed control. Although Harrelson et al. (2007) indicated that all cover crop residues evaluated, which included winter wheat, winter rye, perennial ryegrass, triticale (*×Triticosecale rimpaui* Wittm.), barley, oats (*Avena sativa* L.) and crimson clover (*Trifolium incarnatum* L.), produced acceptable NT pumpkin yields and fruit size, small grain cover crops, such as winter wheat or winter rye, are generally used to suppress weed densities in NT pumpkin production systems (Morse et al. 2001, Walters et al. 2008). The presence of surface residue and lack of soil disturbance in NT pumpkin production were likely contributing factors that significantly influenced weed control even in the absence of herbicides (Walters et al. 2008). In NT pumpkin production systems, sparse or unevenly distributed cover crop residues often result in fields having high weed densities that lead to low pumpkin yields and poor fruit quality (Morse et al. 2001). Several studies have indicated that although broadleaf weed control is improved, herbicide-killed winter rye will not effectively suppress many broadleaf weeds in NT pumpkin production even if used in conjunction with a standard herbicide program (Rapp et al. 2004, Walters & Young 2010, Walters et al. 2008). Weed densities in pumpkin vary with environmental conditions, tillage strategy, and amount of cover crop residue (Rapp et al. 2004). Although crop residues provided by herbicide-killed winter wheat or winter rye will improve grass and broadleaf weed control, the densities of many difficult to control broadleaf weeds (e.g., many *Amaranthus* spp.) in NT pumpkin production at harvest remain similar to those produced in bare soil. Winter rye or winter wheat cover crop residues alone will provide some, but insufficient weed control for pumpkins grown in NT (Walters et al. 2008, Walters & Young 2010).

The production of high-residue, evenly distributed mulches over the soil surface can enhance weed suppression in NT pumpkins, which can often reduce or even eliminate the need for PRE herbicides (Morse et al. 2001). In growing seasons with high weed pressures, winter rye residues without herbicide application were effective in suppressing weed populations in pumpkins for only about 6 to 7 weeks after planting (Rapp et al. 2004). Walters et al. (2008) found that redroot pigweed and common waterhemp control in NT pumpkins was achieved early in the growing season with only winter rye residues, but control was not

sustained throughout the growing season. Pumpkin productivity in NT production systems was highly correlated with giant foxtail (*Setaria faberi* Herrm.), common cocklebur, redroot pigweed, and total weed control, with correlations indicating that pumpkin yields increased with greater weed control (Walters et al. 2008). Furthermore, pumpkin fruit number and weight, as well as average fruit size were correlated with both early- and late-season control of all weed species ($0.47 \geq r \leq 0.86$, $P \leq 0.01$; Walters et al. 2008).

The lack of effective herbicides has hindered the adoption of NT pumpkin production. Weed control is essential to obtain the highest possible pumpkin yields in NT production systems and tank mixtures of various herbicides are generally necessary to maximize weed control (Brown & Masiunas 2002, Kammler et al. 2008). Although weeds are a major problem in pumpkin NT production systems, there are a limited number of registered herbicides available for weed control. The majority of herbicides registered for pumpkins are used PRE and provide limited control of broadleaf weeds and nutsedge (Grey et al. 2000, Brown & Masiunas 2002) and are often ineffective when weather conditions are not ideal for activation. Several registered herbicides including clomazone + ethalfluralin, halosulfuron-methyl and S-metolachlor have made NT more successful, since cultivation is not an option in this type of production system. Walters et al. (2008) found that PRE use of clomazone + ethalfluralin or clomazone + ethalfluralin with halosulfuron-methyl tended to improve weed control in a NT, winter rye residue production system. Galloway & Weston (1996) found that ethalfluralin applied alone provided only short term weed suppression with control observed for only 4 to 5 weeks after application. Rapp et al. (2004) found that PRE application of ethalfluralin and halosulfuron, provided effective weed control in a NT winter rye residue production system.

Walters & Young (2008) indicated that although cover crops, such as winter wheat or winter rye, can be integrated into NT pumpkin production systems along with labeled herbicides to improve weed control, improvement in weed management systems beyond current practices and available herbicides is still necessary to maximize pumpkins yields. In NT pumpkin production systems, the potential yield reduction from herbicide injury does not outweigh the yield gains that are provided by reliable and effective weed control (Rapp et al. 2004, Walters et al. 2008). Thus, the judicious use of herbicides is an important part of any effective weed management program for NT pumpkin.

4.3 Tomato

The few studies on NT tomato production systems have provided conflicting results. Although Beste (1973) indicated that yields of direct seeded processing tomatoes grown in NT were similar to those grown in CT, Doss et al. (1981) reported that marketable staked tomato yields decreased in NT compared to CT. However, Shelby et al. (1988) indicated that the use of NT is a feasible alternative to CT for tomato production, since staked tomato yields in CT were generally comparable to yields obtained in NT. Furthermore, staked tomatoes in a NT hairy vetch mulch system yielded higher than CT tomatoes (Abul-Baki & Teasdale 1993). The production of fresh-market tomatoes in NT hairy vetch residue has been successful in providing high economic returns, especially in regards to reducing herbicide and nitrogen inputs (Teasdale 1999).

Fall-seeded winter rye can be used as a weed management tool in NT tomato production, as tomato yields using winter rye residues were comparable to treatments without winter rye, provided that weed control was sufficient (Smeda & Weller 1996). Masiunas et al. (1995) indicated that winter rye residues in reduced tillage cropping systems can provide weed

control and tomato yields similar to those in CT systems that have had a pre-plant incorporated (PPI) soil application of trifluralin and metribuzin. Furthermore, the non-selective herbicide, glyphosate, that was used to kill the winter rye, also resulted in eliminating any existing winter annual weeds, which tended to result in similar or higher tomato yields compared to those obtained by just mechanical mowing of the winter rye. However, in most field situations, additional POST weed management would be necessary to maintain control of weeds through the critical weed-free period (about 6 weeks after transplanting) for tomato, although in some instances, winter rye residues can suppress weeds for up to 60 days after transplanting (Masiunas et al. 1995).

The availability of several POST herbicides for both broadleaf and grass weed control in tomato (Table 2) provides a greater overall potential to achieve optimum weed control compared to many other vegetable crops. Although many PRE or pre-transplant herbicides are available for use in tomato, the availability of POST herbicides are important to control later emerging weeds that can affect both yields and harvest efficiency. In NT tomato, redroot pigweed and morningglory control at 68 and 93 DAT was adequate with POST applications of metribuzin (Shelby et al. 1988). Sequential POST metribuzin applications followed by a POST grass herbicide in NT tomato provided adequate broadleaf and grass weed control that resulted in high marketable yields. These sequential POST applications in NT tomato production mimic the use of cultivation in CT tomato to provide effective late season weed control.

5. Summary and conclusions

The effectiveness of NT production systems depends on the vegetable crop grown, the crop establishment method, establishment of high residue mulch from a cover crop on the soil surface, and available PRE and POST herbicides for the vegetable crop. NT systems seem to work better in those vegetables that: 1) have vines that rapidly spread across the soil surface (e.g., cucumber and pumpkin) which suppress weed growth; 2) provide rapid canopy closure (e.g., broccoli planted on narrow rows) to prevent weed growth; or 3) have several labeled PRE and POST herbicides that will provide both early-and late-season broadleaf and grass weed control. Often times, vegetable crops that are transplanted into NT produce greater yields than those that are direct seeded. For example, cabbage yield reductions in NT were related more to poor plant establishment than to the effects of a NT production system (Willhot et al. 1990). In most vegetable production systems, sparse or unevenly distributed cover crop residues on the soil surface often result in fields having high weed densities that lead to low yields and often poor fruit quality. In NT systems, high-residue cover crop mulches can suppress weed growth and often reduce or even eliminate the need for applied herbicides (Morse 2001). The inclusion of cover crops in vegetable production systems will not only improve weed control (Teasdale 1999), but will also conserve soil moisture, increase soil organic matter content, and provide other soil conservation advantages (Johnson & Hoyt 1999). Additionally, alternative tillage systems, such as NT, can further extend vegetable production into regions that are highly erodible.

Although cover crops contribute to weed control in NT production systems, herbicides or other weed control tactics are generally required to obtain optimal weed control and crop yield. The use of labeled PRE and POST herbicides is important to achieve optimum weed control in NT vegetable production. The use of PRE herbicides is important for early-season weed control in vegetable crops; and, although there are several PRE herbicides available for

many different vegetable crops, the emergence of weeds after soil residual herbicides have dissipated often leads to excessive weed populations later in the production season. There are only a few POST herbicides labeled for broadleaf weed control for NT vegetable crops. This lack of effective POST herbicides is a major limiting factor in NT vegetable production systems (Hoyt et al. 1994), as the effective control of annual grasses and broadleaf weeds by POST herbicides is important to achieve success in this type of production system. Although grass weeds can be effectively controlled in most vegetable crops with PRE and POST herbicides, many difficult to control broadleaf weeds are often not sufficiently controlled due to the lack of effective herbicides that can be applied POST.

Since high weed populations are generally observed in NT production systems, weed control is essential to obtain the highest possible vegetable yields in this type of production system. The use of cultural practices that promote better vegetable crop establishment, more rapid plant growth and canopy closure will also result in improved weed suppression and high crop yields. Although NT systems utilizing cover crops are becoming more common for many vegetable crops, the major limitation for widespread grower limitation of NT practices is weed management. Thus, fields that have weed problems should be avoided or weed densities should be reduced in some manner prior to using NT production practices; and, if necessary, herbicides may have to be used during the production of the cover crop to minimize weed populations before transplanting (Morse 1999a). Cover crop mulch residues contribute to weed control in integrated weed management systems for NT crop production, but a major issue for growers is that they require more intensive management than CT systems. Although results from most studies have indicated that improvement in weed management systems beyond current practices and available herbicides is still required to maximize vegetable productivity in NT production systems, cover crop residues integrated in NT vegetable production systems along with the judicious use of herbicides can potentially suppress weeds in NT vegetable production and provide yields similar to CT.

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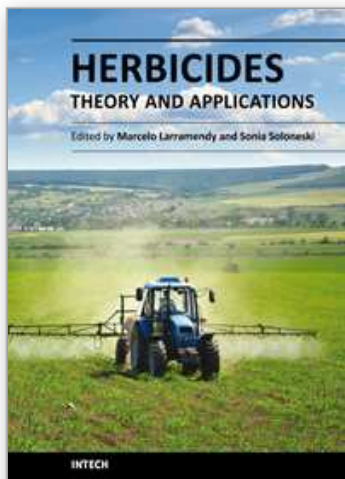
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The content selected in Herbicides, Theory and Applications is intended to provide researchers, producers and consumers of herbicides an overview of the latest scientific achievements. Although we are dealing with many diverse and different topics, we have tried to compile this "raw material" into three major sections in search of clarity and order - Weed Control and Crop Management, Analytical Techniques of Herbicide Detection and Herbicide Toxicity and Further Applications. The editors hope that this book will continue to meet the expectations and needs of all interested in the methodology of use of herbicides, weed control as well as problems related to its use, abuse and misuse.

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